Thermal Evolution and Light Curves of Young Bare Strange Stars

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We study numerically the cooling of a young bare strange star and show that its thermal luminosity, mostly due to e^+e^- pair production from the quark surface, may be much higher than the Eddington limit. The mean energy of photons far from the strange star is $\sim 10^2$ keV or even more. This differs both qualitatively and quantitatively from the thermal emission from neutron stars and provides a definite observational signature for bare strange stars. It is shown that the energy gap of superconducting quark matter may be estimated from the light curves if it is in the range from ~ 0.5 MeV to a few MeV.

Strange stars that are entirely made of deconfined quarks have been long ago proposed as an alternative to neutron stars (e.g., [1]). The bulk properties (size, moment of inertia, etc.) of strange and neutron stars in the observed mass range ($1 < M/M_\odot < 2$) are rather similar, and it is very difficult to discriminate between strange and neutron stars [2]. Strange quark matter (SQM) with a density of $\sim 5 \times 10^{14}$ g cm^{-3} might exist up to the surface of a strange star [3]. This differs qualitatively from the neutron star surface and opens observational possibilities to distinguish strange stars from neutron stars.

Normal matter (ions and electrons) with a mass $\Delta M \lesssim 10^{-5} M_\odot$ may be present at the SQM surface of a strange star [3]. Such a massive envelope of normal matter could completely obscure the quark surface. However, a strange star at the moment of its formation is very hot. The temperature in the stellar interior may be as high as a few times 10^{11} K [4, 5]. The rate of neutrino-induced mass ejection from such a hot compact star is very high [6]. Therefore, in a few seconds after the star formation the normal-matter envelope is blown away, and the SQM surface is nearly (or completely) bare [7]. A strange star remains nearly bare as long as the surface temperature is higher than $\sim 3 \times 10^7$ K [8].

Due to the high plasma frequency of SQM, $\omega_p \sim 20$ MeV, a bare strange star will be a very inefficient emitter of thermal X-rays as soon as its temperature drops below $\sim 10^{11}$ K, i.e., a few seconds after it is born [3]. This fact suggested that bare strange stars would be very difficult to detect. However, the enormous surface electric field, which binds the electrons to the quark matter, will induce intense emission of e^+e^- pairs [9] and subsequent hard X-ray emission, at luminosities above the Eddington limit, $L_{\rm Edd} \simeq 1.3 \times 10^{38}(M/M_\odot)$ erg s^{-1}, as long as the surface temperature is above $\sim 5 \times 10^8$ K [7]. This process significantly increases the possibility to detect young bare strange stars, but its importance depends on how long a high luminosity can be sustained.

We want to address this issue in this letter by modeling in detail the thermal evolution of a young bare strange star in order to calculate its light curve, considering various scenarios about the state of SQM. It should be emphasized that the resulting evolution described here will differ both qualitatively and quantitatively from the evolution of a strange star with a crust, i.e., covered by a small layer of normal matter, [10], and from the evolution of a more standard compact object [11].

Recently, it has been argued that SQM is a color superconductor with a very high critical temperature $T_c \sim 10^{12}$ K (for reviews, see [12]). At extremely high density the color superconductor is in the "Color-Flavor-Locked" (CFL) phase in which quarks of all three flavors and three colors are paired in a single condensate. In this CFL phase SQM is electrically neutral and no electrons are present. If the strange quark mass, m_s, is not too large the CFL phase may extend down to the lowest density corresponding to the surface of a strange star, in which case the considerations of this paper are irrelevant since no electrons would be present at the surface and hence there would be no supercritical electric field and no e^+e^- pair emission. However, for sufficiently large m_s the low density regime is rather expected to be in the "2 color-flavor SuperConductor" (2SC) phase in which only u and d quarks of two color (say u_1, u_2, d_1 and d_2) are paired in a single condensate while the ones of the third color, say u_3 and d_3, and the s quarks of all three colors are unpaired. In the 2SC phase electrons are present. We will consider strange stars made entirely of normal, i.e., unpaired, SQM, which may be unrealistic but is a benchmark and the case of SQM in the 2SC phase only and with a mixture of 2SC phase with CFL phase at high density and, finally, SQM in the 2SC phase with secondary pairing of the u_3-d_3 and s quarks with a much smaller gap. In all cases the critical temperature is related to the energy gap $\Delta(0)$ at $T = 0$ through $T_c \simeq 0.57\Delta(0)$ as in BCS theory (in natural units $\hbar = c = k_B = 1$).

We consider, as a typical case, a 1.4 M$_\odot$ strange star which we construct by solving the Tolman-Oppenheimer-Volkoff equation of hydrostatic equilibrium using an equation of state for SQM as described in [2, 3] [with a bag constant $B = (140\text{MeV})^4$, QCD coupling constant $\alpha_s \equiv g^2/4\pi = 0.3$, and $m_s = 150$ MeV]. The thermal

evolution is determined by the energy conservation and heat transport equations:

$$C_v \frac{\partial T}{\partial t} = -\frac{1}{4\pi r^2}\frac{\partial(4\pi r^2 F_r)}{\partial r} - Q_\nu \ \ \text{and} \ \ F_r = -\kappa\frac{\partial T}{\partial r} \quad (1)$$

where C_v is the specific heat of the matter, κ its thermal conductivity and Q_ν its neutrino emissivity, and F_r is the heat flux at radius r. We are actually solving the general relativistic version of these equations with a Henyey-type cooling code [13]. At the stellar surface, the heat flux directed outward the strange star is equal to the energy flux emitted from the stellar surface, $F_r(r = R) = F_\gamma + F_\pm$, where F_γ and $F_\pm$ are the energy flux emitted from the unit surface of SQM in thermal photons and e^+e^- pairs, respectively. This and equation (1) give the boundary condition on $\partial T/\partial r$ at the stellar surface. The boundary condition at the stellar center is $\partial T/\partial r = 0$. In our numerical simulations, we adopt the values of F_γ and $F_\pm$ from [7]. We assume that at the initial moment, $t = 0$, the temperature in the strange star is uniform, $T = 10^{11}$ K ~ 10 MeV.

The specific heat is $C_v = C_v(e) + \sum_q C_v(q)$ (q running through the nine quark components, $u_1, ..., s_3$) with $C_v(i) = \frac{1}{3}\mu_i^2 T$, μ_i being the chemical potential of the ith component. When a component i becomes paired its $C_v(i)$ first increases by a factor 2.426 at T_c and then decreases exponentially at $T \ll T_c$ [14].

The neutrino emission is due to the three quark direct Urca processes $u_c + e^- \to d_c + \nu_e$ and $d_c \to u_c + e^- + \overline{\nu}_e$, $c = 1$, 2, 3 denoting the quark color which is not altered by weak interactions, with emissivities [15]

$$Q_\nu^c \simeq 3\times10^{25}\alpha_s\left[\frac{\mu_u\,\mu_d}{(400\text{MeV})^2}\frac{\mu_e}{10\text{MeV}}\right]T_9^6 \ \text{erg cm}^{-3}\,\text{s}^{-1} \quad (2)$$

and the corresponding, but weaker, processes with $d_c \leftrightarrow s_c$. These processes are also strongly suppressed when one of the participating component is paired [16].

The thermal conductivity is an essential ingredient of our calculations since it determines how fast heat is carried to the surface from the underlying layers. When no quark pairing is present κ has been calculated in [17]:

$$\kappa^{\text{N}} \simeq 1.7 \times 10^{21}\frac{(\mu_q/400\text{MeV})^2}{\alpha_s} \ \text{erg s}^{-1}\text{cm}^{-1}\text{K}^{-1}. \quad (3)$$

In the case of the 2SC phase the thermal conductivity will be provided dominantly by the unpaired quarks u_3 and d_3 which only suffer scattering through the exchange of the fully screened (both Debye and Meissner) gluon of adjoint color index 8 [18]. Following the method of [17] we obtain

$$\kappa^{\text{2SC}} \simeq 3.5\times10^{22}\frac{(\mu_q/400\text{MeV})^3}{\alpha_s^{1/2}\,T_9} \ \text{erg s}^{-1}\text{cm}^{-1}\text{K}^{-1}. \quad (4)$$

In the CFL phase the thermal conductivity is extremely large [19] because this phase is transparent to photons, $\kappa^{\text{CFL}} \sim 10^{30} \times T_9^3 \ \text{erg s}^{-1}\text{cm}^{-1}\text{K}^{-1}$.
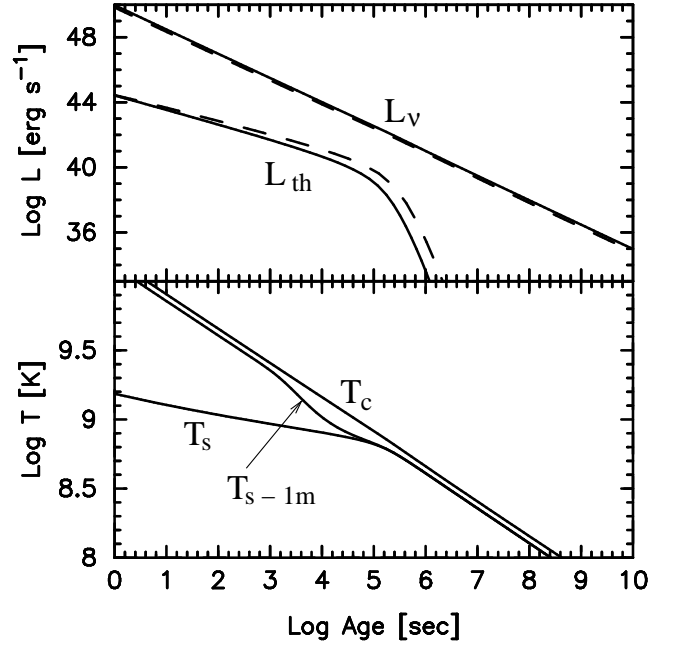

FIG. 1: Upper panel: luminosities in neutrinos, L_ν, and photons plus e^+e^- pairs, L_{th}, for a strange star in the normal phase (solid lines) and in the 2SC phase (dashed lines). Lower panel: temperature in the center, T_c, at the surface, T_s, and 1 meter below the surface, T_{s-1m} of the strange star in the normal phase. The large difference between T_s and T_{s-1m} at early times illustrates the enormous temperature gradient present just below the surface because of the large L_{th}.

Figure 1 shows the temperature and luminosities (in both neutrinos and surface thermal emission) as a function of time t, for a strange star in the normal phase and in the 2SC phase with a gap $\Delta_{2SC} \sim 100$ MeV. The neutrino luminosity, L_ν, is always much higher than the surface thermal luminosity, L_{th}, i.e., neutrinos drive the cooling and the surface emission just follows the evolution of the bulk of the star. The occurrence of the 2SC phase has little effect on the star's evolution: the reason is that the neutrino emission is cut by a factor three since u and d quarks of color 1 and 2 do not contribute anymore, and the specific heat is cut by a factor 9/5. The neutrino cooling time scale is $\tau_{\text{cool}} \sim C_v T/Q_\nu$ (see Eq. (1)), and it therefore does not change significantly.

We see that the thermal luminosity may be many orders of magnitude higher than the Eddington limit for a period of several days after the strange star formation. Such a high luminosity is allowed for a bare strange star because at its surface SQM is bound via strong interaction rather than gravity and, therefore, a bare strange star is not subject to the Eddington limit in contrast to a neutron star [3, 9]. Super-Eddington luminosities are a fingerprint of hot bare strange stars. At $t > 10^5$ s, the thermal emission decreases fast, and after about one month when $T_s < 3 \times 10^8$ K, the thermal radiation becomes practically undetectable (see Fig. 1). This strong

decrease of the surface emission is due to the suppression of the e^+e^- pairs emission by increasing degeneracy of electrons in the thin "electron atmosphere" [7].

Assumption that a part of the interior of the strange star is paired in the CFL phase, with $\Delta_{\mathrm{CFL}} > 10$ MeV, has no effect at all on the surface thermal luminosity. The reason is simply that it cuts down both Q_ν and C_v in the same fraction and does not affect τ_{cool} at all. We have checked it numerically with a mass of up to 1.39 $M_\odot$ of the star, for a total mass of 1.4 $M_\odot$, in the CFL phase and found variations in L_{th} smaller than the thickness of the line in the plot of Fig. 1. The star's temperature profile is of course affected since the CFL core cools mostly by heat diffusion into the outer 2SC phase layer, but neutrino emission in this outer layer is so strong that T_s and L_{th} are practically not affected. This result is similar to the case of quark matter in neutron star interiors which is undetectable if it is in the CFL phase [11].

Two effects can dramatically alter the results of Fig. 1. They are a secondary pairing of the u_3 and d_3 quarks, and also possibly of the s quarks, in the 2SC phase, and convection in the upper layers [20].

Pairing of the u_3 and d_3 quarks, in addition to the 2SC pairing, will quench the 3rd color channel of neutrino emission by the direct Urca process of Eq. 2 and reduce the specific heat while pairing of the s quarks will have little effect on the neutrino emission but will reduce C_v. The suppression of Q_ν and C_v is very strong only if the resulting gap is nodeless, while a gap with nodes on the Fermi surface will only produces a reduction of the order of $(T/T_c)^2$ if nodes are at isolated points and of order of T/T_c if nodes are 1D lines. The cooling time scale, τ_{cool}, can be increased or reduced depending on whether Q_ν or C_v is the most strongly suppressed. Since very little is known on these possible secondary gaps (see however [21]) we consider three cases for the u_3-d_3 gap Δ_3 and the s gap Δ_s: [A] $\Delta_3 = 0.3$ Mev and $\Delta_s = 3$ MeV, [B] $\Delta_3 = \Delta_s = 3$ MeV, and [C] $\Delta_3 = 3.0$ Mev and $\Delta_s = 0.3$ MeV. These three cases span a large range of suppression of Q_ν and/or C_v.

Figure 2 shows the resulting range of L_{th} possibly attained through this secondary pairing. We assumed nodeless gaps to maximize the effects, but have verified explicitly that gaps with nodes give results which are intermediates between the three cases presented here. Case [A] has very little Q_ν suppression and only partial reduction of C_v, and it naturally differs little from the case of no pairing. Cases [B] and [C] have strong Q_ν suppression and their cooling is eventually driven by the surface thermal emission. Since case [B] also has a strong C_v reduction it cools faster than case [C] whose C_v is more moderately suppressed. The knees on the curves [B] and [C] at times $t \sim 10^7$ sec and $t \sim 3 \times 10^{10}$ sec, respectively, correspond to the moment when the star becomes almost isothermal.

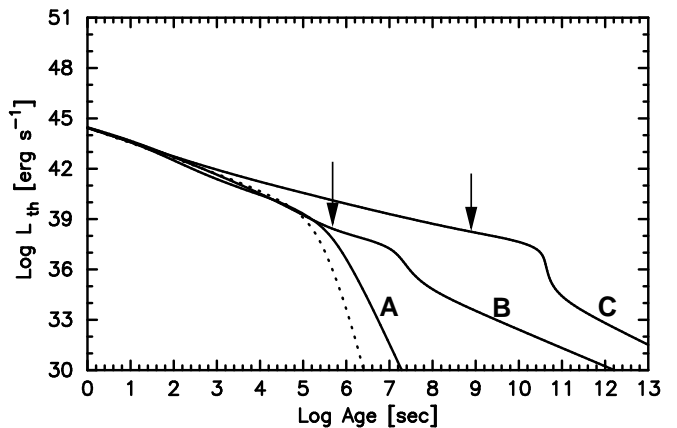In all the models presented above, at early times, the

FIG. 2: The thermal luminosity of the strange star in the 2SC phase with secondary pairing of the u_3-d_3 and s quarks for three different scenarios of pairing [A], [B] and [C] as described in the text (solid lines). Arrows on curves [B] and [C] point the time at which L_ν becomes lower than L_{th}; in case [A] $L_\nu \gg L_{\mathrm{th}}$ at all times. The dotted line shows the evolution of L_{th} without any pairing for comparison (from Fig. 1).

temperature gradient just below the surface (see Fig. 1, lower panel) is many orders of magnitude higher than the adiabatic temperature gradient [22]

$$\left.\frac{dT}{dr}\right|_{\mathrm{ad}} \cong \frac{T}{3n_q}\frac{dn_q}{dr} = \frac{T}{\mu_q}\frac{d\mu_q}{dr} \sim 300 \times T_9 \ \mathrm{K\,cm}^{-1} \quad (5)$$

where n_q is the quark number density. If convection can develop, given the shallowness of the superadiabatic layer we can, as a first approximation, consider the star as having a uniform temperature. Moreover, in the case of pairing of the u_3-d_3 quarks, and/or s quarks, we may expect convective counterflow of the u_3-d_3, and/or s, superfluid which may be even more efficient that convection to erase any temperature gradient.

Figure 3 shows the resulting range of L_{th} for isothermal stars for the same three cases of secondary pairing as in Fig. 2. In cases [B] and [C], a few seconds after the star formation the u_3-d_3 pairing occurs and subsequently $L_\nu < L_{\mathrm{th}}$ while in case [A] neutrino losses drive the cooling during all times. The sharp drop of L_{th} in case [B] at $t \sim 20$ s is due to the strong suppression of C_v from pairing and does not occur in cases [A] and [C] in which the u_3-d_3 or s gaps are smaller. At early times the isothermal models have a much higher thermal luminosity that the diffusive ones of Fig. 2 since their surface temperature is much higher. However, the isothermal models whose cooling becomes driven by thermal emission, [B] and [C], cool faster and eventually have a lower L_{th} than the diffusive ones. Naturally, isothermal and diffusive models follows the same evolution once the latter become isothermal, i.e., after the knees of cases [B] and [C] in Fig. 2.

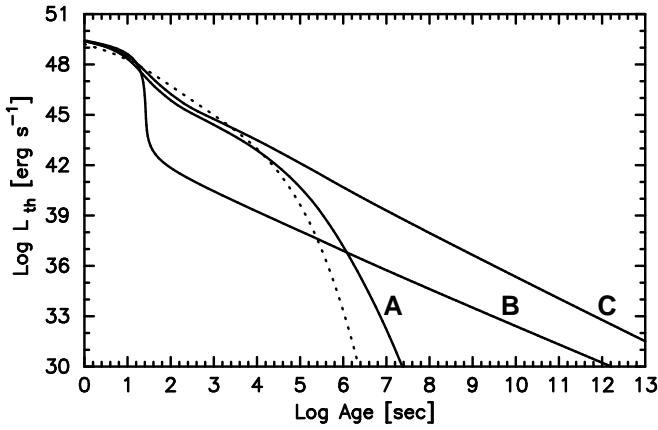How much the density dependence of the chemical

FIG. 3: The thermal luminosity for the same scenarios as in Fig. 2. It is assumed that the star is isothermal due to either convection or superfluid counterflow. The dotted curve shows the evolution of L_{th} without any pairing for comparison.

composition of SQM, and of the pairing gaps, may reduce convection, and superfluid counterflow, is an open question and precludes us to firmly decide which cooling trajectories, Fig. 2 or 3, are the correct ones. However, the gradients of both μ_i's and Δ's are small in SQM and one may expect only small reductions, i.e., the isothermal models of Fig. 3 are probably more appropriate that the diffusive ones of Fig. 2.

In our simulations we assumed that neutrinos escape freely from the stellar interior. This is valid only in a few seconds after the strange star formation when the internal temperature is less than $\sim 10^{10}$ K [5]. In this case, e^+e^- pairs created at the surface of SQM prevail over photons in the surface thermal emission [7] but pairs outflowing from the stellar surface mostly annihilate into photons in the vicinity of the strange star [7, 23].

In the process of the star cooling the photon spectrum varies significantly. At very high luminosities, $L_{\text{th}} > 10^{43}$ ergs s^{-1}, we expect that the photon spectrum is nearly blackbody with a temperature $T_{\text{BB}} \simeq T_0(L_{\text{th}}/10^{43}$ erg s$^{-1})^{1/4}$, where $T_0 \simeq 2 \times 10^8$ K [24]. For intermediate luminosities, $10^{41} < L_{\text{th}} < 10^{43}$ erg s^{-1}, the effective temperature of photons is more or less constant, $T_{\text{BB}} \sim T_0$ [23]. At $L_{\text{th}} < 10^{41}$ erg s^{-1}, the photon spectrum essentially differs from the blackbody spectrum, and its hardness increases when L_{th} decreases. This is because photons that form in annihilation of e^+e^- pairs do not have enough time for thermalization before they escape from the strange star vicinity. When the photon luminosity decreases from $\sim 10^{41}$ erg s^{-1} to $\sim 10^{36}$ erg s^{-1}, the mean energy of photons increases from ~ 30 keV to ~ 500 keV while the spectrum of photons eventually changes into a very wide ($\Delta E/E \sim 0.3$) annihilation line of energy $E \sim 500$ keV [23]. Such a variability of the pho-

ton spectrum together with the light curves calculated in this paper could be a good observational signature of a young bare strange star.

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